

# Solar Wind Turbulence Models Evaluated via Observations of Doppler RMS Phase Fluctuation and Spectral Broadening in the Inner Corona

A. L. Berman  
TDA Engineering Office

*The modelling of doppler noise (RMS phase fluctuation) has enjoyed considerable success via the experimentally observed proportionality between doppler noise and integrated electron density. Recently, theoretically derived models for doppler noise have been proposed. These models are broadly characterized as representing proportionality between doppler RMS phase fluctuation ( $\phi$ ) and particle flux. Under the assumptions of conservation of particle flux in the solar wind and proportionality between electron density and electron density fluctuation, these models yield a doppler noise dependence upon signal closest approach point ( $a$ ) of:*

$$\phi \propto a^{-1.5}$$

*Doppler noise observations in the inner corona ( $r_{\odot} \lesssim a \lesssim 5r_{\odot}$ ) are shown to conclusively demonstrate that doppler noise is proportional to integrated electron density ( $\sim a^{-5}$ ), and not  $a^{-1.5}$ , as predicted by the particle flux models. Similarly, spectral broadening in the inner corona is seen to be proportional to integrated density. The article concludes that the particle flux models are in disagreement with the experimental observations of doppler noise to date, and hence are unlikely to be representative of actual solar wind processes.*

## I. Introduction

Berman and Wackley (1976, Ref. 1) have experimentally demonstrated that doppler noise (RMS phase fluctuation) is proportional to signal path integrated electron density. Recently, other investigators have derived theoretical expressions for the radial dependence of doppler noise. Callahan (Ref. 2) has derived such an expression for doppler noise, and Woo (Ref. 3) has both derived such an expression for and

analyzed doppler noise ("Doppler Scintillation"). These independent efforts have resulted in somewhat similar models, which can be broadly characterized in terms of the dependence of doppler RMS phase fluctuation ( $\phi$ ) upon signal closest approach point ( $a$ ) as:

$$\phi \propto \text{particle flux} \cdot a^{0.5}$$

applying the conservation of particle flux in the solar wind and assuming proportionality between electron density and electron density fluctuation, one directly obtains:

$$\phi \propto (a^{-2}) \cdot a^{0.5} = a^{-1.5}$$

This article examines the performance of these models (hereafter to be referred to as the “particle flux models”) in respect to the experimental observations of doppler noise in both the extended corona ( $5r_{\odot} \lesssim r \lesssim 1\text{AU}$ ;  $r_{\odot}$  = solar radius,  $r$  = radial distance) and inner corona ( $r_{\odot} \lesssim r \lesssim 5r_{\odot}$ ), and concludes that the particle flux models are incompatible with the experimental observations to date. At the same time, these doppler noise observations continue to strongly support the proportionality between doppler noise and integrated electron density (hereafter to be referred to as the “integrated density model”) as espoused by Berman and Wackley.

## II. The Particle Flux Models

Evaluation of Eq. (24) from Callahan (Ref. 2) yields for the primary term:

$$\phi \propto n(a)v(a)a^{0.5}$$

where:

$n$  = electron density fluctuation

$v$  = solar wind radial velocity

If one assumes the conservation of particle flow in the solar wind (Cuperman and Harten, Ref. 4):

$$K = N_e(r)v(r)r^2$$

where:

$N_e$  = electron density

in combination with the common assumption of proportionality between electron density and electron density fluctuation:

$$N_e(r) \propto n(r)$$

one directly obtains for doppler noise

$$\phi \propto (a^{-2}) \cdot a^{0.5} = a^{-1.5}$$

Simplification of Eq. (14) from Woo (Ref. 3) yields for doppler noise:

$$\phi \propto n(a)[v(a)]^{5/6} a^{0.5}$$

Considering  $v^{5/6} \approx v$  (as Ref. 3 does) and assuming conservation of particle flow and proportionality between electron density and electron density fluctuation, one immediately obtains:

$$\phi \propto a^{-1.5}$$

By far the most interesting feature of these particle flux models is their absolute insensitivity to the radial dependence of (integrated) electron density! It is precisely this feature of the particle flux models which allows a straightforward evaluation via comparison to experimental observations of doppler noise in the vastly different regimes of the inner and extended corona. Briefly stated, the radial dependence of electron density is well known to change from  $r^{-6}$  to  $\sim r^{-2.3}$  in the transition from the inner to the extended corona. The particle flux models predict that doppler noise will not “detect” this abrupt change in electron density; correspondingly, the integrated density model predicts that doppler noise will exactly mirror the sharp change in electron density.

## III. Model Evaluation in the Extended Corona

To date, the only highly precise and mathematically objective determination of the radial dependence of doppler noise in the extended corona is Berman, Ref. 5. This study found the radial *index* to be  $-1.30$  ( $a^{-1.30}$ ), which corresponds to a  $(-\infty, \infty)$  integration of  $r^{-2.30}$ . Since the average radial dependence of electron density in the extended corona found by a variety of experimentors is approximately  $r^{-2.3}$  (Ref. 6), the results of Ref. 5 strongly support the integrated density model. Figure 1 (from Ref. 5) shows the results of a simultaneous two parameter least squares minimization to the (extended corona) coefficient and radial index. Although observations of doppler noise in the extended corona as portrayed in Fig. 1 clearly favor the integrated density model over the particle flux models, the difference between  $a^{-1.30}$  and  $a^{-1.5}$  is not large in absolute terms, and hence the extended corona results cannot be considered dramatically conclusive. Fortunately, the inner corona, with its abrupt shift

in the radial dependence of electron density, allows no such ambiguity. The data must conclusively favor one model over the other.

#### IV. Model Evaluation in the Inner Corona

Inner corona electron density observations via both eclipse photometry methods (van de Hulst, Ref. 7; Saito, Ref. 8; and Blackwell, Ref. 9) and spacecraft range delay measurements (Muhleman (Mariner 6) Ref. 10; Edenhofer (Helios 2), Ref. 11) show an extremely sharp change in electron density radial dependence at approximately  $r = 4r_{\odot}$ . The corresponding breakpoint for signal path integrated electron density is approximately  $a = 3r_{\odot}$ . Since the particle flux models are independent of electron density, one would expect no change in the doppler noise radial dependence at  $a = 3r_{\odot}$ . Figure 2 presents doppler noise observations for the region  $2r_{\odot} \leq a \leq 6r_{\odot}$ ; included in Fig. 2 is the integrated density model of Berman (ISEDC) and the particle flux model of Callahan. There is no question but that experimental observations of doppler noise in the inner corona “sense” the sharp increase of integrated electron density at  $a \approx 3r_{\odot}$ . To this author it is an inescapable conclusion that the particle flux models simply do not correctly predict experimental observations of doppler noise, and hence their derivations cannot be considered representative of actual solar wind processes.

#### V. Spectral Broadening in the Inner Corona

Woo (Ref. 12) has derived a model for the spectral broadening ( $B$ ) of a monochromatic spacecraft signal which is quite similar to the particle flux model of Ref. 3 (actually  $\phi = B^{5/6}$  from Ref. 3). Therefore, just as for doppler noise, spectral broadening observations in the inner corona should not (according to Ref. 12) detect the onset of the inner corona electron density enhancement. To date, Rockwell (Ref. 13) has performed the only highly precise and mathematically objective study of spectral broadening radial dependence in the inner corona. Reference 13 achieved excellent results in fitting spectral

broadening data via use of a model resembling integrated electron density. Figure 3 presents the data from Ref. 13; included in Fig. 3 are the individual “inner corona” and “extended corona” components from Rockwell’s model. The important point is that the two components become equal valued at  $a \approx 3r_{\odot}$ , and hence spectral broadening data “sense” the change in electron density exactly as does doppler noise (and quite significantly, at the same radial distance). The clear fact that spectral broadening data are in good agreement with integrated electron density in the inner corona provides a most powerful refutation of the particle flux models for *both* RMS phase fluctuation and spectral broadening.

#### VI. Conclusions and Discussion

Recent attempts to theoretically derive the parametric form of doppler noise have produced (“particle flux”) models which are independent of (integrated) electron density. The inner corona, with its vastly distinct electron density regimes, provides a most powerful test bed to assess the validity of the particle flux models. Experimental observations of doppler noise in the inner corona dramatically respond to the abrupt change in electron density regimes, and hence it must be concluded that the particle flux models do not model actual solar wind processes. Similarly, observations of spectral broadening in the inner corona mirror the doppler noise observations, and hence provide even further fortification of the negative evaluation of the particle flux models. It is an inexorable conclusion of this article that both RMS phase fluctuation and spectral broadening are proportional to integrated electron density, and not, as has been suggested, particle flux.

The importance of this conclusion should not be overlooked. With proportionality to integrated electron density, doppler noise represents a most powerful experimental tool for obtaining the radial dependence of both electron density and solar wind radial velocity; were the particle flux models correct, then doppler noise would be far less useful as a radio science data type.

## References

1. Berman, A. L., and Wackley, J. A., "Doppler Noise Considered as a Function of the Signal Path Integration of Electron Density," in *The Deep Space Network Progress Report 42-33*, Jet Propulsion Laboratory, Pasadena, California, 15 June 1976.
2. Callahan, P. S., "A First-Principles Derivation of Doppler Noise Expected From Solar Wind Density Fluctuations," in *The Deep Space Network Progress Report 42-42*, Jet Propulsion Laboratory, Pasadena, California, December 15, 1977.
3. Woo, R., "Radial Dependence of Solar Wind Properties Deduced from Helios 1/2 and Pioneer 10/11 Radio Scattering Observations," in *The Astrophysical Journal*, 219, January 15, 1978.
4. Cuperman, S., and Harten, A., "Some Physical Implications of Recent Solar Wind Measurements," in *Solar Wind*, edited by Sonett, C. P., Coleman, P. J. Jr., and Wilcox, J. M., National Aeronautics and Space Administration, Washington, D.C., 1972.
5. Berman, A. L., Wackley, J. A., Rockwell, S. T., and Kwan, M., "Viking Doppler Noise Used to Determine the Radial Dependence of Electron Density in the Extended Corona," in *The Deep Space Network Progress Report 42-38*, Jet Propulsion Laboratory, Pasadena, California, 15 April 1977.
6. Berman, A. L., "Electron Density in the Extended Corona: Two Views," in *The Deep Space Network Progress Report 42-41*, Jet Propulsion Laboratory, Pasadena, California, October 15, 1977.
7. van de Hulst, J. C., "The Electron Density of the Solar Corona," *Bulletin of the Astronomical Institutes of The Netherlands*, Volume XI, Number 410, February 2, 1950.
8. Saito, K., "A Non-Spherical Axisymmetric Model of the Solar K Corona of the Minimum Type," *Annals of The Tokyo Astronomical Observatory*, University of Tokyo, Second Series, Volume XII, Number 2, Mitaka, Tokyo, 1970.
9. Anderson, J. D., Esposito, P. B., Martin, W. L., Thornton, C. L., and Muhleman, D. O., "Experimental Test of General Relativity Using Time Delay Data from Mariner 6 and Mariner 7," in *The Astrophysical Journal*, Volume 200, August 15, 1975.
10. Muhleman, D. O., Esposito, P. B., and Anderson, J. D., "The Electron Density Profile of the Outer Corona and the Interplanetary Medium from Mariner 6 and Mariner 7 Time Delay Measurements," *The Astrophysical Journal*, 211, February 1, 1977.
11. Edenhofer, P., Esposito, P. B., Hansen, R. T., Hansen, S. F., Lueneburg, E., Martin, W. L., and Zygielbaum, A. I., "Time Delay Occultation Data of the Helios Spacecrafts and Preliminary Analysis for Probing the Solar Corona," in the *Journal of Geophysics* 42, 1977.
12. Woo, R., Yang, F., and Ishimaru, A., "Structure of Density Fluctuations Near the Sun Deduced from Pioneer-6 Spectral Broadening Measurements," in *The Astrophysical Journal*, Vol. 210, No. 2, December 1, 1976.
13. Rockwell, S. T., "An Empirical Spectral Bandwidth Model for Superior Conjunction," in *The Deep Space Network Progress Report 42-43*, Jet Propulsion Laboratory, Pasadena, California, 15 February 1978.

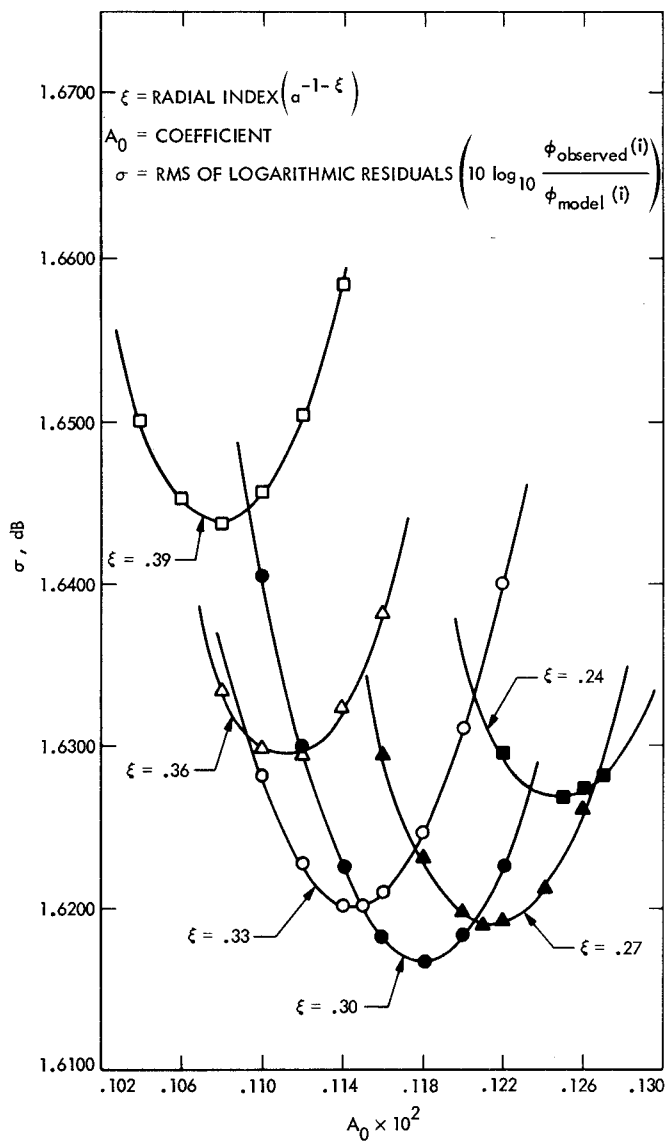


Fig. 1. Viking S-Band Doppler noise fit in the extended corona

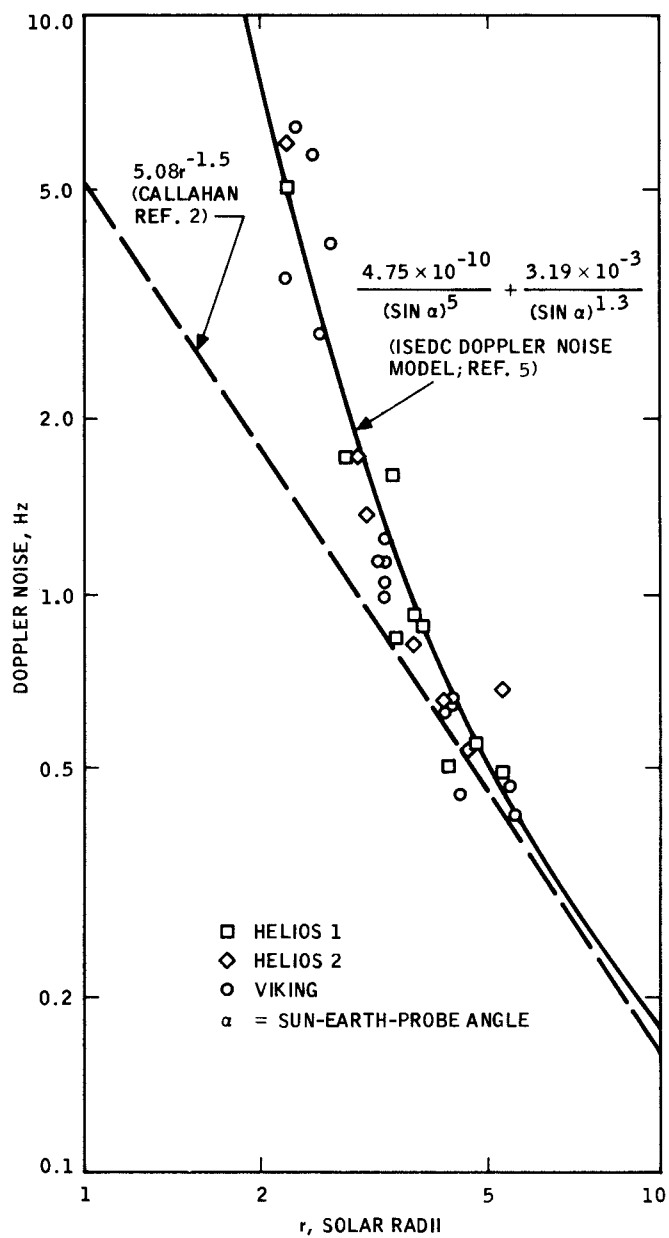
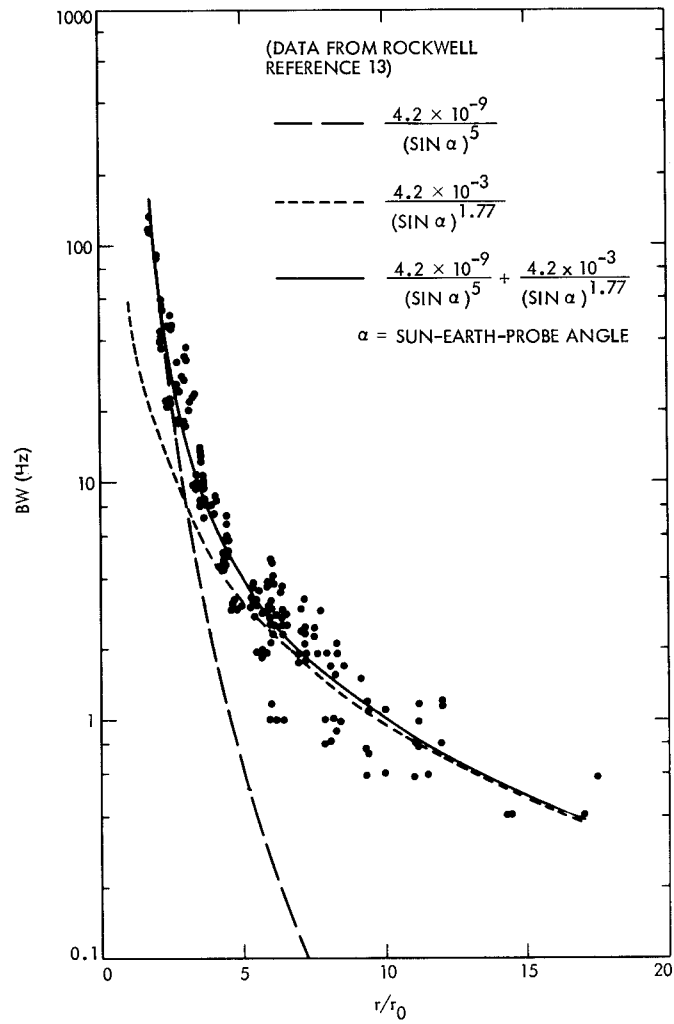


Fig. 2. Doppler noise models in the inner corona



**Fig. 3. Spectral broadening data in the inner corona**